

Giant molecular clouds in M 33: are they susceptible to dynamical friction?

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ABSTRACT

Most of giant molecular clouds (GMCs) in M 33 are connected with spiral-like gaseous arms (filaments) with the exception of the inner 2 kpc region where the link between the arms and GMCs disappears (see Tosaki et al. 2011). We check whether it may be caused by the dynamic friction retarding the clouds. Using semi-analytical model for this galaxy we calculate the dynamics of GMCs of different masses situated at different initial galactocentric distances in the disk plane. We demonstrate that the dynamical friction may really change the orbits of GMCs in the central 2 kpc-size region. However in this case the typical lifetimes of GMCs should be close to or greater than 10^8 yr, which is larger than the usually accepted values.

Key words: galaxies: kinematics and dynamics, galaxies: ISM, ISM: clouds

1 INTRODUCTION

Giant molecular clouds (GMCs) are the most massive bodies in galactic discs. The physical process of their formation from the more rarefied gas is the matter of debate, although it seems evident that there is no universal mechanism of transition of HI to H₂. It may happen either through gas flow collisions, or by the process of slow contraction of a cloud from diffuse atomic or molecular medium (see, e.g. Dobbs & Pringle 2013). Observations clearly show that in the case of contrast spiral arms such as observed in M 51, GMCs are concentrated in the arms, although less massive clouds are dispersed both along the arms and in between, giving evidence that molecular clouds may survive when passing through spiral arms (see review by Koda 2013). In the low luminous galaxies such as LMC, SMC or M 33 the situation is different: GMCs are usually connected with HI filaments which means that most of their lifetime they move parallel with HI. How long do they live is another question. It is usually accepted that GMCs have a relatively short lifetime $10^6 - 3 \cdot 10^7$ yr (several free-fall times) and are disrupted by stellar feedback soon after the beginning of star formation (Dobbs & Pringle 2013; Dobbs et al. 2014; Murray 2011). However there are arguments that at least a fraction of GMCs in galaxies may live as long as about 10^8 yr or more (see discussion in Koda 2013; Scoville 2013; Zasov & Kasparova 2014). It is worth noting that the feedback effec-

tiveness of disrupting of a cloud is badly known. Numerical simulations of evolution of GMCs demonstrate that the gas outflows from the feedback may reduce the mass of the cloud but do not destroy it in case of the weak thermal feedback (Tasker et al. 2015). However another numerical simulations (e.g. by Williamson et al. (2014) show that GMCs could be destroyed by the stellar feedback.

It is evident that the dynamical evolution of GMCs depends on their existence as single entities. In the case of their long lifetime one can expect that the dynamical friction may be unavoidable in the inner part of a disc leading to the radial migration of gas toward the centre of a galaxy. This scenario was first proposed by Sil'chenko & Lipunov (1987). Later this idea was applied to the Milky Way in the frame of 2D analytical model of MW by Yasutomi & Tatematsu (1990). In turn Jogee et al. (1999) proposed the dynamic friction of very massive gas clumps observed in the bar of starburst galaxy NGC 2782 as the mechanism forcing the gas to inflow to the centre of this galaxy. In principle, dynamical friction may be responsible for central gas concentration and stimulation of starforming or AGN activities in some gas-rich galaxies.

Slowly rotating galaxy with low contrast spiral structure such as M 33 may be a good laboratory to test the dynamical evolution of GMCs. Miura et al. (2012) estimated a lifetime of GMCs in M 33 by comparing CO(J=3-2) data and young star ages. They concluded that about 2/3 of all GMCs have the age $\leq 10^7$ yr, although the age of the rest clouds is 10 – 30 Myr. However one should have in mind

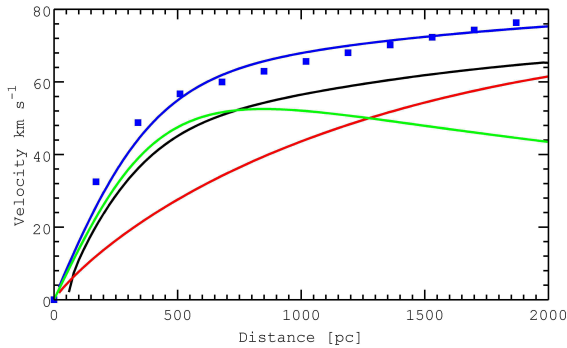


Figure 1. Model fit of the rotation curve decomposition for M 33 for the inner $r = 4$ kpc region: bulge (green) and stellar disc (red) circular velocities. Gas circular motion is represented by blue line. Stellar disc rotation curve is shown by black line. Points represents the observational data following by Corbelli (2003).

that these estimates are not too reliable being based on the visible manifestation of star formation inside of the clouds. In addition the starting point of the detachment of GMCs from the surrounding gas remains rather indefinite (Dobbs & Pringle 2013) especially if taken into account that a significant part of relatively low-dense translucent gas in the outer regions of slowly forming cloud may be non-detected in CO-lines.

Most of GMCs in M 33 are linked with the gaseous spiral-like arms. However in the inner 2 kpc region of this galaxy the tight connection between GMCs and HI filaments disappears (Tosaki et al. 2011), and concentrations of molecular gas look quite detached from HI there. As it was noted by Koda (2013), discussing this result, “GMCs are decoupled from the HI distribution as if they are entities that survive through almost a galactic rotation period”. It is worth trying to check whether this decoupling may be explained by the dynamical friction which brakes GMCs moving through the stellar disk and the bulge and forces them to depart from their birthplaces in the gaseous arms. Of course, the result depends on the ratio of the braking time to the typical life time of GMCs. We have developed a numerical model of motion of point-like GMCs in the galactic disc of M 33 and calculated the drag forces which affect the clouds within the radial distance of several kpc. We argue that the spatial offset between GMCs and their birth places (spiral-like filaments) may be accounted for dynamic friction if the lifetime of GMCs is allowed to exceed the period of rotation in the inner disc ($\sim 10^8$ yr).

The paper is organized as the following. The second Section contains a basic model description including both the equation of cloud motions and the initial parameters of simulations. In the third Section the main results are described. The last Section contains the discussion and summary.

2 THE MODEL

We designed a simple kinematics model of the GMCs motion through the stellar components of the galaxy. A cloud is considered as a particle m_c moving through the sea of “stellar” particles of mass $m_* \ll m_c$ whose spatial distribution reproduces the spherical bulge component and the

galactic disc. As a basic model, we used the model presented by Saburova & Zasov (2013), which is based on the rotation curve of M 33 and stellar velocity dispersion of disc stars, where the density of disc was calculated using the condition of its marginal stability. Similar density distribution of a stellar disc was found in the more sophisticated mass model developed by Corbelli et al. (2014). Although there is no strict evidences of the classical bulge in M 31 (see discussion in Corbelli & Walterbos 2007), Regan & Vogel (1994) found the excess of spherically distributed light fitted by $r^{1/4}$ law with the effective radius ≈ 8 arcsec ≈ 2 kpc, which may be attributed to the bulge or inner stellar halo. This excess fits the shape of rotation curve in the inner region of M 33 (Saburova & Zasov 2012). The only change we have done in our calculations is the replacement of de Vaucouleurs bulge by Plummer sphere with mass $10^8 M_\odot$ and scale length 0.6 kpc. Note however that the resulting force of dynamical friction is determined mostly by the disc (see below), being not sensitive to the bulge parameters. The exponential stellar disc is characterized by the central surface density $800 M_\odot \text{pc}^{-2}$, radial scale 1.9 kpc and vertical scale length 200 pc. Stellar velocity dispersion in the model corresponds to the disc scale height.

As it is shown in Fig. 1, our model satisfactory reproduces the velocity curve of the inner part of the galaxy. We do not consider the dark halo separately, but it is worth noting that its relative mass is low in the considered region, and, moreover, the role of dark matter is inseparable from the role of bulge-like spherical component. We assume the rigid non-evolved model of the spherical component and galactic disc that allows to avoid the direct self-consistent N-body simulations.

To describe a dynamics of massive particles (clouds) we have used a several well-known relations relevant to the dynamical friction. The equation of motion has the form:

$$m_c \frac{\partial^2 \mathbf{r}}{\partial t^2} + \beta \frac{\partial \mathbf{r}}{\partial t} + \frac{V_c^2}{r^2} \mathbf{r} = 0, \quad (1)$$

where \mathbf{r} is a cloud radius vector, $\beta = \beta_d + \beta_b$ is a drag coefficient by the disc and spherical components and V_c is a circular velocity supported by the gravitational potential of these components.

For the general case of massive cloud motion the Chandrasekhar’ dynamical friction formula can be written in the form:

$$\beta = \frac{16\pi^2 \ln \Lambda m_c (m_c + m_*)}{v^3} \int_0^\infty f(\mathbf{r}, \mathbf{u}) \mathbf{u}^2 d\mathbf{u}. \quad (2)$$

where $f(\mathbf{r}, \mathbf{u})$ is the phase-space distribution function, m_* is the mass of a star, m_c is the mass of a cloud. If the low mass particles are distributed in the disc with exponentially decreasing radial profile of the density, then the drag force is proportional to the coefficient (Benson et al. 2004):

$$\beta_d = \frac{3\pi G \ln \Lambda \rho_0 m_c^2}{(\sqrt{2}\sigma)^3}, \quad (3)$$

where ρ_0 is the local disc volume density and σ is the velocity dispersion of stars.

For the case of Plummer sphere, representing the stellar spherical component, the drag coefficient may be written in the following form (Chatterjee et al. 2002):

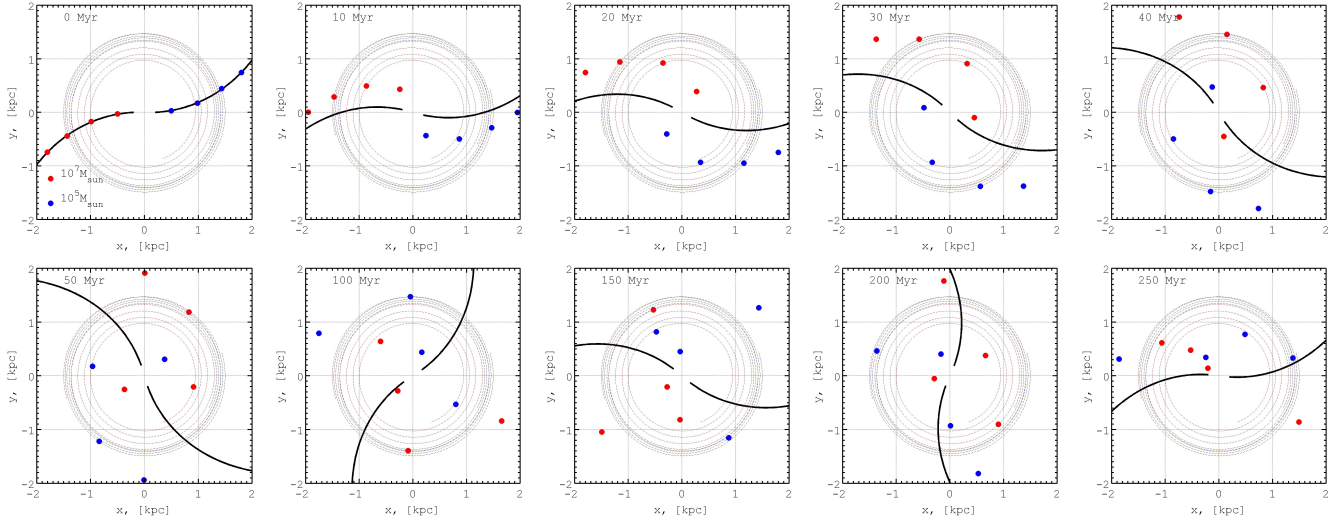


Figure 2. Time sequence of the cloud positions for the clouds of $10^5 M_\odot$ (blue) and $10^7 M_\odot$ (red) in the fixed reference system. Black lines mark a spiral structure rotating rigidly with an angular velocity $25 \text{ km s}^{-1} \text{ kpc}^{-1}$. Dashed lines are the cloud tracks beginning from the initial position $r_0 = 1500 \text{ pc}$.

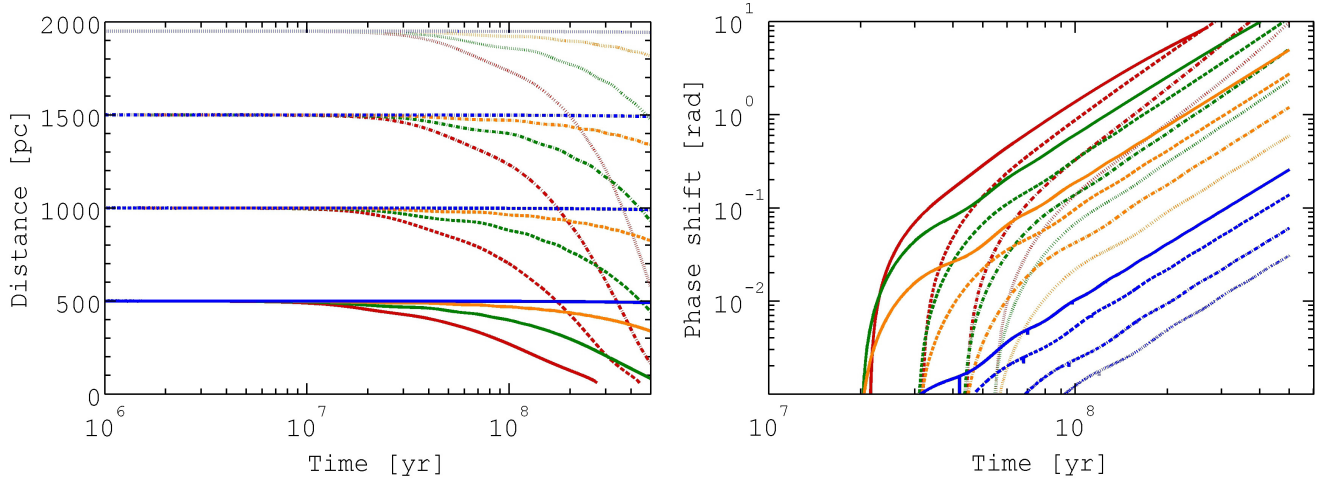


Figure 3. Left: evolution of galactocentric distance r for clouds with masses 10^4 (deep blue), 10^5 (orange), 10^6 (green), 10^7 (red) solar masses. Right: azimuthal shift of the cloud position from the initial azimuth angle according to Eq. 7.

$$\beta_b = \frac{128\sqrt{2}}{7\pi} \ln \Lambda \left(\frac{G}{M_b a} \right)^{1/2} m_c^2, \quad (4)$$

where M_b is the mass of spherical component and a is its scale length.

Following Tremaine & Weinberg (1984), we take the Coulomb logarithm Λ as

$$\Lambda = \frac{b_{max}}{b_{min}}, \quad (5)$$

where $b_{min} = \max(Gm_{cl}/V_0^2, 2R_{cl})$, V_0 is a typical cloud velocity with respect to stars, R_{cl} is the cloud radius. Distance interval, b_{max} is taken as the radius of gravitational influence of a given cloud. In the calculations we assume $b_{max} = 2 \text{ kpc}$.

3 CALCULATIONS

We studied the dynamics of clouds with masses in the range $10^4 - 10^7 M_\odot$ in the inner part of M 33, consisting of the disk and spherical components. We also took into account a finite size of clouds, assuming that they have a constant surface density, so that a cloud linear size is linked with its mass by the simple relation

$$m_{cl} = 200 R_{cl}^2 \quad (6)$$

according to the third Larson's law (Larson 1981), which was obtained for molecular clouds of the Milky Way and is applicable to nearby galaxies. The size of clouds was used for calculation of the logarithmic term in the dynamic force expression. Initial orbital velocities of the clouds were taken as the circular velocities at a given radius corresponding to the gravitational potential model for a given circular velocity curve (see Fig. 1). The motion of GMCs was described by Eq. 1 for clouds with the constant mass in the

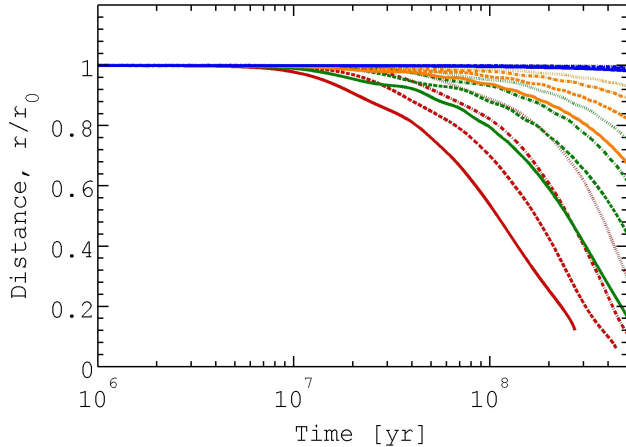


Figure 4. Evolution of the galactocentric distances of GMCs normalized to the initial distances. Notations are the same as in **Fig. 3**.

range $10^4 - 10^7$ solar masses (M_\odot) during the time interval up to 5×10^8 yr. Initial radial coordinates were chosen as $r_0 = 500, 1000, 1500, 2000$ pc.

Although the HI and CO-maps of M 33 reveal a spiral-like structure, the Grand Design wave-like nature of spiral arms in this galaxy remains very controversial: see Regan & Wilson (1993); Cepa & Beckman (1990); Rosolowsky et al. (2007). Non-direct measurements of the corotation radius under the assumption of rigid-body rotation of spiral arms carried out by different authors led to a large spread of the estimates between 2.9 kpc and 5.9 kpc (Scarano & Lépine 2013), which corresponds to the angular velocity of spiral pattern Ω_p between 18 and 33 $\text{km s}^{-1} \text{kpc}^{-1}$. Selecting the middle value of $\Omega_p = 25 \text{ km s}^{-1} \text{kpc}^{-1}$, we show in Fig. 2 the expected shift of GMCs and spiral pattern in the differentially rotating disc as it is seen in the fixed reference coordinate system (the effect of dynamic friction is included). The initial angular velocity of every cloud corresponds to the observed rotation curve of M 33 at a given initial radius r_0 . The azimuth angle initially taken as φ changes as :

$$\delta\varphi = \varphi - \Omega_0(r_0)t \quad (7)$$

where φ is a true polar coordinate of a cloud and $\Omega_0(r_0) = \frac{V_c(r_0)}{r_0}$ is the initial angular cloud speed. Fig.2 clearly illustrates that the lifetime of GMCs should be very short (about 10^7 yr) to allow them to remain linked with spiral arms. Otherwise the observed connection between GMCs and the spiral like gaseous structure gives evidence of flocculent (“material”) nature of spiral arm in the inner several kpc-region of M 33.

During the first 10 Myr after their formation all clouds practically retain their initial circular orbits. After that their orbital radii decrease due to the loss of angular momentum by dynamical friction. As one can expect, more massive clouds fall down to the center much faster than the less massive ones. Note that the clouds of equal masses starting from the larger distances change their orbital radii faster than the clouds formed closer to the centre (see Fig. 4). After $\approx (1 - 3) \times 10^8$ yr the azimuthal shift with respect to the initial azimuth angle for massive clouds reaches $180 - 360^\circ$

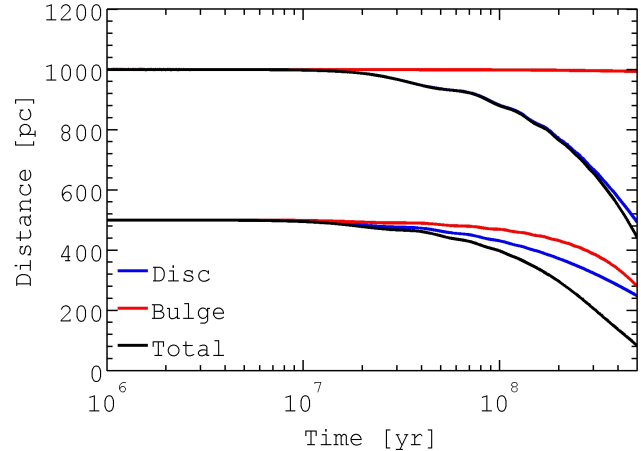


Figure 5. Evolution of galactocentric distance of a cloud with the mass $10^7 M_\odot$ in the models where the drag is due to the bulge (red), or the disc (blue) only, and the combined action of both components (black). The latter case was illustrated in Fig. 3.

(see Fig. 3). **Fig. 4** illustrates the variation of radial distances of clouds normalized to the initial radius r_0 . One can see that the relative change of radial coordinate depends both on the initial distance and a cloud mass. The increasing of drag force at lower radial distances is the result of the increasing of the disc density and of the growing influence of spherical bulge component.

To check the relative role of the components we calculate GMCs drift assuming $\beta_d = 0$ (the disc is absent) or $\beta_b = 0$ (the bulge is absent). As an illustration, in Fig. 5 we trace the dynamics of massive ($10^7 M_\odot$) cloud for the initial distances 1000 and 500 pc. For a cloud starting far away from the center the stellar bulge impact in the total radial shift is incredibly small. However in the central 500 pc the bulge plays a significant role (up to 30%) due to its enhanced density, however the stellar disc remains the dominant factor of the clouds migration there.

A significant fraction of GMCs in M 33 is observed between radial distances $r = 2 - 4$ kpc. A major amount of them have $M < 3 \cdot 10^5 M_\odot$ (Rosolowsky et al. 2007). Most of these GMCs are evidently situated near their birthplaces inside of the not-too-regular gaseous spiral-like filaments. We have not calculate the drag force for these outer clouds to clarify how their position may changed during $\approx 10^8$ yr of their lifetimes, however the obtained results for $r \approx 2$ kpc demonstrate that the dynamic friction does not shift them significantly from their nearly circular orbits. Indeed, for the cloud masses $10^5 - 10^6 M_\odot$ at the initial distant 2 kpc the change of radial distance is about 100 – 150 pc ($< 40''$) during 10^8 yr after their formation (see Fig. 3), which is comparable with the typical width of HI filaments they are embedded. The mass function of GMCs in M 33 is very steep: $dN M^{-2} dM$ (Rosolowsky et al. 2007) with the mass truncation at $10^6 M_\odot$, hence the radial shift due to dynamic friction may be noticeable only for a few most massive GMCs at $r > 4$ kpc — and only if they remain non-disrupted for that time interval. Note however that the shift between GMCs and spiral arms would be significant even after much shorter time interval 10^7 yr, if the angular velocity of spiral pattern and of the disc in a given galactocentric interval were

different, as it is illustrated in Fig 2. We consider this circumstance as the argument in favor of flocculent nature of gaseous filaments, leaving the question of wave-like nature of the most prominent stellar arms in M 33 open.

4 CONCLUSIONS

As it was demonstrated above, GMCs we considered in our model (with the exception of the most distant and less massive ones) change significantly their positions after 10^8 yr due to dynamical friction. The key role in this process is played by the disk.

We may conclude that the dynamical friction may naturally explain the loss of connection between GMCs and spiral-like gaseous filaments in the inner 2 kpc in M 33. In turn it allows us to avoid the assumption that GMCs observed in this region were formed beyond the gas filaments in contrast to the more distant counterparts. If this approach is correct, it leads to three important conclusions.

- Lifetimes of GMCs (at least in the inner region of M 33) should be close to or exceed 10^8 yr for the friction to be efficient (see the discussion of the long lifetime of molecular clouds in Zasov & Kasparova 2014).
- Spiral-like gaseous arms containing GMCs should also be long-lived features, otherwise the observed GMCs would not be tightly linked to the arms at the distances $r \geq 2$ kpc.
- Gaseous spiral arms in M 33 do not rotate rigidly, otherwise a significant fraction of GMCs would have observed in the inter-arm space (see Fig 2). As long as the positions of most GMCs coincide with gaseous arms at radial distances 2-4 kpc, one may conclude that they move together with the gas, that is the gaseous arms are not the wave-like phenomena. Note that the flocculent nature of spiral arms in M 33 was argued earlier by different authors (see e.g. Cepa & Beckman 1990; Regan & Wilson 1993; Rosolowsky et al. 2007). This conclusion is correct at least within the galactocentric radius $r \approx 4$ kpc: beyond that distance GMCs are nearly absent in spite of the existence of molecular gas (Rosolowsky et al. 2007).

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